Post-breakage behaviour of laminated glass in structural applications

Didier Delincé, Dieter Callewaert, Jan Belis, Rudy Van Impe
Laboratory for Research on Structural Models (LMO), Ghent University, Belgium
Didier.Delincé@Ugent.be, www.LMO.UGent.be

Firstly is introduced what the post-breakage behaviour of laminated safety glass is, and why it's important to can model it for designing structural glass elements. A general description of post-breakage behaviour and the different possible mechanisms leading to failure are presented. We then focus on the mechanical properties of the interlayer material, more specifically in the perspective to model its behaviour at large strain up to break. Typical results of standard uniaxial tensile tests on SGP samples (SentryGlas® Plus, interlayer of DuPont de Nemours) are shortly presented, and we then explain why those are insufficient to calibrate numeric material models to use in finite elements softwares. Finally perspectives for further experimental investigation with aiming to calibrate material models are presented.

Keywords: laminated glass, interlayer, polymer, post-breakage, material behaviour, structural application

1. Introduction

Laminated glass is used since a few decades in the building industry, during which its range of applications and performances has widened, from "simple" safety glazing (resistance to impact, burglar resistance,…) to use as structural elements (e.g. floors, stairs, glass fins,…).

Laminated safety glass is considered to be "safety glass" in the sense that the broken pieces of glass are still bonded to the transparent plastic interlayer(s) in case of glass breakage. The first and up till now most-used interlayer material is PVB (polyvinyl butyral), which is produced by different manufacturers. Some manufacturers propose different grades of PVB. However, new products have been developed the last years to improve the global performances of laminated glass products in function of the requirements for specific building applications.

One of those products, probably one of the best-known currently, is SGP (SentryGlas® Plus, a stiffer "structural" interlayer by DuPont de Nemours). The lamination process is very similar for SGP and PVB. The most significant practical difference is that SGP films are delivered in plates, while the PVB films are delivered in rolls. This material is known to be stiffer than usual PVB; table 1 shows typical comparative mechanical properties published by the producer. Differences in mechanical behaviour will be further discussed later in this article.

Other interlayer materials, a.o. in the form of cast resins, claim also better structural performances than a usual PVB. In the product standard EN 14449 for laminated glass [5], a distinction is made between products fabricated with cast resins and those laminated with a plastic film.

Table 1: Mechanical properties of interlayer polymer: indicative values [1]

Property	unit	PVB	SGP
Volumetric weight (density)	kg/m³	1070	950
Elastic modulus	N/mm²	18	300
Tensile strength	N/mm²	> 20	34,5
Deformation at breakage	%	> 250	400
Glass transition temperature T_g *	°C	~10-15°C	~55-60°C

* values of glass transition temperature T_g reported in [9] for PVB and in [4] for SGP

However, it is often not evident for the designer to determine in which case the use of another interlayer material than "common" PVB – generally more expensive – brings a quantifiable benefit for a particular, non-standard application. On the one hand side it depends on the configuration itself and its corresponding performance requirements; on the other hand side it depends on the availability of validated design models that can be used to evaluate the performances of different laminated glass products. Consequently, a better understanding of the mechanical behaviour of laminated glass is important, in particular to evaluate the benefits of using such specific interlayer materials.

For the design of a structural element, the following two complementary aspects have to be evaluated : the *probability of failure* and the corresponding *consequence of failure*. For structures including laminated glass elements, we can then distinguish the evaluation of the resistance, corresponding to propagation of the first crack in any of the glass layers (probability of failure), and the post-breakage behaviour, corresponding to the state in which one or more glass sheets are broken and the broken glass pieces are still bonded to the interlayer (consequence of failure). An example of practical post-breakage stadium is shown in figure 1 for a glass floor where the upper thermally toughened glass ply is broken.

A conceptual frame of a combined probability-consequence based approach for the safety requirements of laminated glass elements has been proposed in [3]. The evaluation of the post-breakage behaviour principally means that one has to check that the damaged laminated glass element can retain a certain amount of load during a certain period of time.

In the following sections we present some aspects related to the development and the validation of models for the post-breakage behaviour that could be used by designers to evaluate at lower costs the mechanical performances of laminated glass products used in particular configurations, essentially in structural applications. The material modelling of the polymer material used as interlayer is then discussed.

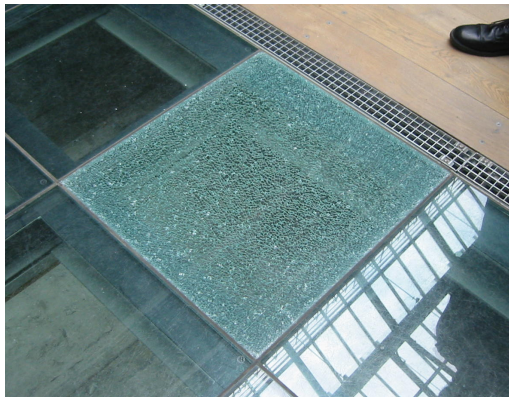

Figure 1: Practical example of post-breakage stadium :
a floor element in laminated glass with the upper ply broken is expected to show residual resistance

2. Overview of post-breakage behaviour of laminated safety glass

As mentioned here above, the post-breakage stadium of laminated glass is defined as the state when one or more glass sheets are cracked and the broken glass pieces are still bonded to the interlayer. Actually, the breakage of the glass plies can be caused by various effects : local impact (from a hard object), overall impact (explosion…), thermal shock, static load, etc. In any case, the evaluation of the post-breakage behaviour is of importance for safety aspects, to avoid consequences of collapse of the cracked element, before it has been replaced.

The evaluation of the post-breakage behaviour of laminated safety glazing is up till now usually investigated by means of experiments. The methods and the criteria are varying depending on the considered standard, but the underlying principles are similar. The evaluated post-breakage performances concern on the one hand side the ability of the interlayer to hold the pieces of glass after it has cracked, and on the other hand side the ability to prevent the passing of an object of specified dimensions through the cracked glazing. In the European standardization frame, a laminated glass, according to the product standard EN 14449 [5], is considered as a *laminated safety glass* if it reaches a minimal class for the pendulum test. The pendulum test is described in the standard EN 12600 [6]; the classification is done on the basis of an evaluation of the two mentioned post-breakage performances. Other specific test standards exist to evaluate more specifically burglar resistance, resistance to explosion, etc.

All those experimental methods are mainly focusing on the performances of laminated glass used as glazing, mounted vertically in a closed frame along its edges, and for rather dynamic breakage conditions. However, those methods appear insufficient to extrapolate the post-breakage behaviour – in rather static conditions – for other configurations, e.g. for non-vertical elements, for other clamping of fixing boundaries, etc. as it is used in particular for structural applications. In that case, the post-breakage behaviour has nowadays generally to be evaluated experimentally, due to the lack of predictive models.

In most cases a laminated glass element in the post-breakage stadium collapses under a bending effort, which can act parallel or perpendicular to its plane. The failure of the element can then be due to one or to a combination of several of the following phenomena :

1) the stretching up to rupture of the interlayer under tensile (or shear) force,
2) the delamination (debonding) between the glass pieces and the interlayer under shear,
3) the splitting up of the glass in the contact zones where the glass pieces scrape against each other.

The importance of those three mechanisms on the post-breakage behaviour greatly depends on the configuration of the element, i.e. the shape (geometry), the boundary conditions and the loading type. Figure 2 shows the local working principle round a crack, in the particular case of bending about the weak axis.

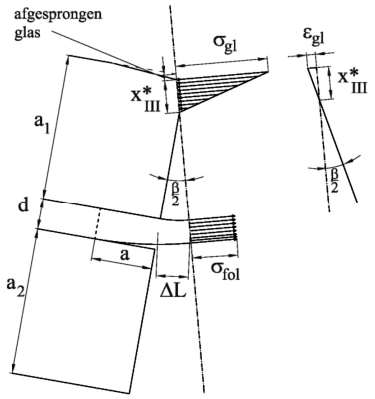

Figure 2: Model of the local post-breakage behaviour round a crack under bending about the weak axis [7]

According to various researches, carried out most of the time on laminated glass with a PVB interlayer, the most important parameters ruling the post-breakage behaviour appear to be :

- the mechanical properties of the interlayer, namely the stiffness in static conditions and the toughness in dynamic conditions, taking into account the possible aging effect due to exposure conditions of the laminated glass;
- the adhesion strength between the glass and the interlayer and the debonding behaviour of the interface, which depends mainly on the surfaces of the assembled products and on the lamination process;
- the size of the glass fragments, and more generally the breakage pattern, which depends on the glass type (a.o. principally if the glass has been thermally reinforced – heat-strengthened or thermally toughened glass – or not – annealed glass), and to a lesser extent on the cause of the breakage, principally for annealed glass.

We focus in the following section on the first aspect, the mechanical properties of the interlayer.

3. Mechanical behaviour of the interlayer material

Historically, mechanical properties of the interlayer material were investigated in the context of the research on the mechanical behaviour of laminated glass before the first breakage, where the main contribution of the interlayer is the shear transfer between the glass plies. It is then generally admitted that the behaviour of the PVB can be described with a linear viscoelastic model.

However, for modelling the post-breakage behaviour of laminated glass elements, we are interested to have a model of the interlayer material also for large deformation.

3.1. Linear behaviour before the first breakage

Before the first breakage, the viscoelastic properties of the interlayer in function of loading time and temperature appear of primary importance on the global stiffness of the laminate, principally under bending about the weak axis or under torsion. Different characterization methods of the shear stiffness of the interlayer have been proposed.

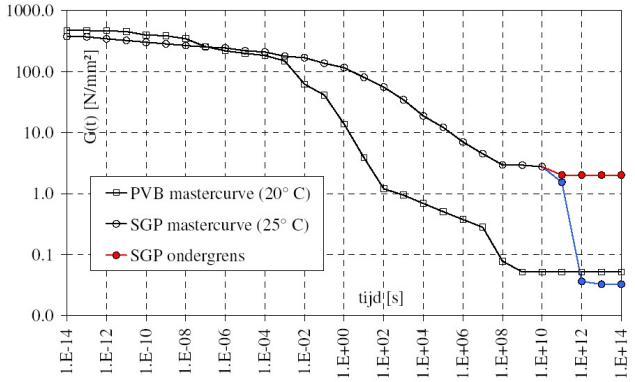

Figure 3: Viscoelastic properties of polymers : mastercurves of PVB and SGP, on basis of data made available by DuPont de Nemours [1]

The producers of interlayer films have generally published the properties of their products based on a dynamic method analysis (DMA). Those tests are carried out on samples of the interlayer film, and the results allow to establish a mastercurve of the shear modulus G in function of time, for a reference temperature. Figure 3 compares such mastercurves for a PVB and the SGP, on the basis of the data made available by DuPont de Nemours (the full data are to be found in [1], the data for PVB originates from [2]). Shift functions are associated to such mastercurves, allowing to derivate viscoelastic behaviour for other temperatures. These shift functions are calibrated on basis of models of equivalency between effects of loading duration and temperature on the viscoelastic reaction of the material.

Other characterization methods have been used, based on relaxation shear tests carried on samples of laminated glass. Such method was used to calibrate a safe general mechanical model for laminated glass with PVB interlayer, assumed to be applicable for all PVB products commonly used in building applications [11].

These models are refered to as linear viscoelastic models, since they are generally only valid for limited deformations of the polymer, typically reached in laminated glass in bending before first breakage.

Such linear viscoelastic models can then be used in numeric finite elements software.

3.2. Non-linear behaviour in post-breakage stadium

In the post-breakage stadium, the interlayer can undergo larger deformations, and then the mechanical properties of the interlayer have to be investigated on a larger working domain, generally including a non-linear (plastic) part under large deformation.

Uniaxial tensile tests on polymer film samples at room temperature (e.g. according to ISO 527 standard) show qualitative differences between the behaviour of PVB and SGP materials (figure 4). This difference in shape between the stress-strain curves of the two materials appears very similar to the one between stress-strain curves of PVB samples above and beneath its glass transition temperature T_g [9]. This observation is coherent with the indicative values of T_g found for PVB and SGP (see table 1). The glass-rubber transition temperature T_g – or simply glass transition temperature – of a polymer corresponds to a progressive change of state in the arrangement of the molecular chains of the polymer.

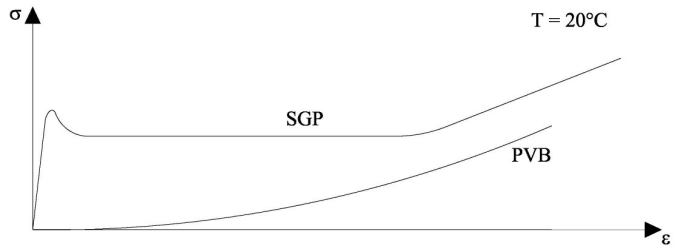

Figure 4: Non-linear mechanical behaviour of polymers : schematic stress-strain curves (nominal values) from uniaxial tensile tests at room temperature (based on tests results of [4], [9] and [10])

The general shape of the stress-strain curve of SGP at room-temperature (figure 4) seems to be characteristic for thermoplastic polymers below or round the glass transition temperature T_g [12], where the polymer behaves rather as a solid (glassy state), with a reversible behaviour at small strains, then a softening part with some irreversible deformations above the yield stress, and finally a reinforcement part (strain hardening) before the breakage. This behaviour is then described as *elasto-viscoplastic*.

Above the glass transition temperature T_g, the polymer behaves rather as a rubber (rubber state), an intermediate state between the solid and the liquid phase that is characteristic for some amorphous polymers, where the viscous component appears to be more important, but their deformation is fully reversible, even at large strain, without any plastic deformation. This is the characteristic behaviour leading commonly to the classification of *elastomer*, and this can be described with *hyperelastic models* (non-linear reversible behaviour at large strain).

In both states (glassy and rubber states), the stress-strain curve appears to be dependent of the strain rate and the temperature.

PVB and SGP are thermoplastic [4]. This means, according to the definition of thermoplastic (in opposition to thermosetting plastics), that they melt when heated, and can be remelted and remoulded. Thermoplastics also loose any permanent plastic deformation when heated above the glass-rubber transition temperature, and recover then their original shape (before the plastic deformation in the glassy state) [12].

Uniaxial tensile tests on SGP material according to test standard ISO 527 were conducted at the laboratory of the Department of Textile of Ghent University. Bone-shaped samples of type 5A, of 2 different thicknesses h (series A : h = 2.40 mm, series B : h = 1.67 mm), were tested at 5 different controlled constant deformation rates (5 – 10 – 20 – 50 – 100 mm/min), at room temperature (temperature of 20°C and relative humidity round 60%). The samples of the series A are conform to the standard, but not those of the series B, since the sample of type 5A are recommended for a sample thickness greater than 2 mm according to ISO 527-2. Figure 5 shows a typical resulting stress-strain curve (engineering or nominal values), and table 2 reports representative values of the serie A.

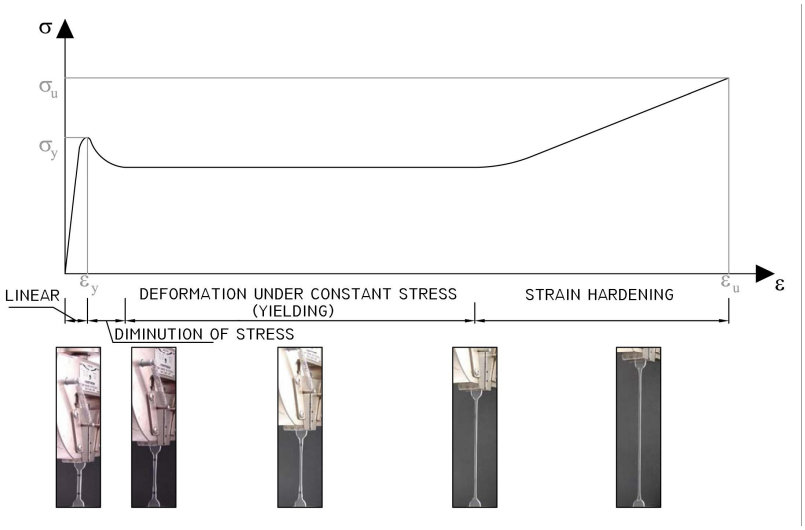

Figure 5: Typical results of uniaxial tensile tests on SPG material at room temperature[7]

The most important observations from the comparison of the results of the series A and B are :

- the number of “bad” breakages, i.e. when the break occurs out of the reference length, is higher within the series B;
- also the dispersion of the stress-strain curves of a same series (same deformation rate) after the yield point is higher within the series B.

The general form of nominal (or engineering) stress-strain curve is these presented on figure 4 (SGP curve). However, the tensile behaviour is showing a local striction of the

transversal section, leading to a progressive necking of the samples that extend on the whole length of the sample under almost constant nominal stress (constant tensile force). This necking is due to the possible strain hardening of the material. This inhomogeneous extension between the used marks to calculate the strain from the experiments happens on the greatest part of the stress-strain curve. The consequence is that the results of those simple uniaxial tensile tests cannot be interpreted to calibrate a true stress-strain "intrinsic" model, even with the assumption of the incompressible deformation of the polymer. More over, this assumption of deformation under constant volume appears as quite correct for rubber behaviour ($T > T_g$), but appears as less correct for the glassy behaviour ($T < T_g$). Those observations are coming from a comparison of the mentioned test results with general analysis of polymers mechanical behaviour [12].

Table 2: Average values of uniaxial tensile tests on SGP material [7]
(serie A : samples of type 5A of ISO 527-2, thickness : 2.40 mm, conditions : T = 20°C and RH ≈ 60%)

s_w *	σ_y	ε_y	σ_u	ε_u
[mm/min]	[N/mm²]	[%]	[N/mm²]	[%]
5	20.97	7.37	33.19	339.43
10	21.86	8.32	34.32	340.53
20	22.40	8.48	32.44	331.25
50	23.79	8.59	33.10	342.33
100	25.09	8.65	35.71	386.56

* s_w : constant deformation rate

4. Conclusions for the material modelling of the interlayer material

We showed why we need a quite accurate model of the interlayer material mechanical behaviour in order to can then model the post-breakage behaviour of laminated safety glass. "Standard" uniaxial tensile tests gave indicative mechanical behaviour of the interlayer material, but appear as insufficient to calibrate an "intrinsic" true stress-strain curve. Possible alternative tests seem to be in first instance advanced uniaxial tensile tests (e.g. with measure of local strain,...) or uniaxial compressive tests [12].

For practical purposes in modelling the post-breakage stadium, a definition of the scope of the material modelling we're interested in is :

- full stress-strain behaviour up to breakage
- temperature range : ~-15°C to ~65°C (this is above and below the glass transition temperature T_g of both PVB and SGP)
- deformation rates : static conditions (for structural behaviour)
- short to middle long "lifetime" – up to replacement of the broken laminated glass element

A classical approach of material research, where the analyse of the macroscopic properties is related to intrinsic properties of the polymer (composition, molecular structure,…) appears as incompatible with industrial protection, and not useful for practical purposes where the most important is to can characterize the properties and mechanical behaviour of a specific product.

More over, others factors are known to have a significant influence on the material behaviour of polymers, a.o. the water content in the polymer, some possible thermal and/or mechanical aging effect.

5. Acknowledgements

This work was supported by the Fund for Scientific Research-Flanders (FWO-Vlaanderen, grant nr. 3G018407). The authors gratefully acknowledge the work of Jeffrey Depauw and the support of prof. Lieva Van Langenhove and ing. Johanna Louwagie from the Department of Textiles of Ghent University. The test samples were helpfully provided by Lerobel, Belgium.

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